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A METHOD OF DETERMINING THE DIMENSIONS AND HORSEPOWER OF AN AIRSHIP FOR ANY GIVEN PERFORMANCE.

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Summary

A simple and easily applied method of calculating the dimensions and horsepower necessary for an airship to have any given performance is described and illustrated by examples. The method includes means for estimating the changes in performance or in size when modifications or new features are introduced into a design, involving increase or saving in weights, or changes in resistance or propulsive efficiency.

The preliminary estimate of the size of an airship to perform any desired duty, such as carrying a given military or commercial load at some given speed and endurance, is based upon two principal sets of data. One set is the proportions of total weight taken by various items, and the other set is the relation between horsepower, speed, and air displacement. The conventional methods of stating such data are not very satisfactory, and new methods are developed for the purpose of this report.

Introduction

It is customary to express the weight items as percentages of the gross lift; but this practice has the two serious objections that the gross lift varies with the kind and purity of the gas used for inflation even when standard atmospheric conditions prevail, and the magnitude of the aerodynamic forces and the resistance depend not upon the gross lift, but upon the total air displacement of the hull. It is therefore proposed to express the weights as percentages of the air displacement, and to use a standard conversion factor or relation between air displacement by weight and by volume. This standard factor is that one cubic foot of air weighs .07635 lb. at sea level, with a temperature of 50°F, and a barometric pressure of 29.92" of mercury. The weights to be considered in the design estimate will then include the item "air and gas."

The relation between horsepower, speed and size may be expressed in the form:

$$HP = \frac{V^3 \ D^{2/3}}{C}$$

Where HP = horsepower,

V = speed,

D = air displacement,

C = a constant determined by data on previous ships.

When C is the Admiralty constant, V is expressed in knots and D in long tons. The magnitude of the constant is a function of the density of the air, and its dimensions are rather awkward and not in line with other aerodynamic calculations. It is proposed to substitute for the Admiralty constant the expression:

$$HP = \frac{V^3 \rho (vol)^{2/3}}{K}$$

where V = speed in ft./sec.,

ρ = density of the air in slugs,

vol = air volume or displacement in ft.^{3}

K is a constant which may be expected to lie between 30,000 and 35,000 in a modern rigid airship, and to be about 20,000 to 25,000 in small nonrigids of less than 200,000 ft.^{3} volume.

Since D, the standard air displacement in pounds, equals .07635 times the volume in ft.^{3}, $(vol)^{2/3} = 5.55\ D^{2/3}$, and

$$HP = \frac{5.55\ V^3 \rho D^{2/3}}{K}$$

Procedure in Finding the Size and Horsepower for an Airship to Carry a Given Load with a Given Speed and Endurance.

The total displacement is divided into items as follows: (1) air and gas, (2) fixed weights exclusive of power plane, power cars, and fuel system, (3) crew, stores, and ballast, (4) power plant and cars, fuel system and fuel, (5) specified military or commercial load. Items (1), (2) and (3) are expressed directly as fractions of D, based on data from existing ships with such corrections as seem reasonable to allow for novel features. Item (4) is expressed in terms of the horsepower, and hence of $D^{2/3}$, and items (4) and (5) together take that fraction of D remaining over from items (1) to (3), inclusive.

Problem 1. Find the volume and horsepower of a rigid airship to carry a military load of 15,000 lb. at 60 knots (101.3 ft./sec.) for 60 hours, 85% of the total volume being filled with helium lifting .064 lb./ft.^{3} (94% pure), in the standard atmosphere.

Since the hull is specified in the conditions of the problem to be 85% full of gas, the weight of the air in the hull is 15% D; and the weight of the gas is 85% D multiplied by the difference between the weights of air and gas per unit volume, and divided by the weight of air per unit volume. The total weight of air and gas is therefore given by

$$\text{Air and gas} = [\,.15 - .85\,(.07635 - .064)/.07635\,] \times D$$
$$= .288\ D.$$

From existing data, the fixed weights exclusive of power plants, power cars and fuel system equal .3D, and the crew, stores and ballast amount to .055 D.

There remains for power plant, fuel and military load

$(1 - .288 - .30 - .055)\ D = .357\ D.$

Assuming the weight of the power plant and its cars to be 8 lb./HP and the weight of the fuel and fuel system to be 0.6 lb.

per horsepower hour, the total weight of power plant, fuel system and fuel is $[8 + (.6 \times 60)]$ HP = 44 (HP). Combining this with the military load,

$$15,000 + 44(HP) = .357\ D \qquad (1)$$

Suppose that from existing data on similar ships,

K = 35,000,

$$HP = \frac{3.55 \times (101.3)^3 \times .00237 \times D^{2/3}}{35,000}$$

$$HP = .39\ D^{2/3} \qquad (2)$$

Combining equations (1) and (2),

$$D - 48\ D^{2/3} = 42,000 \qquad (3)$$

The problem of the size required for a given performance will always reduce to an equation of the form of (3), which may be expressed generally:

$$D - AD^{2/3} = B.$$

The solution for any particular values of A and B may be obtained from the charts (Fig. 1 or 2) by laying a straight edge across these values of A and B on the scales at the left and right hand sides of the chart.

In this problem, A = 48 and B = 42,000, and from the chart, figure 1, D = 215,000 lb., and the air volume = 215,000/.07635 = 2,820,000 ft.^{3}

For convenience in calculating the horsepower, $D^{2/3}$ is plotted against D in figure 3, although it is more accurate, and usually more convenient, to obtain $D^{2/3}$ from a slide rule or a table after finding D. In this case, $D^{2/3} = 3600$, and

HP = .39 × 3600 = 1410.

Problem 2. Find the volume and horsepower of an airship to fulfill the same conditions as in Problem 1, except that the speed is to be 70 knots (118.2 ft./sec.) for 60 hours.

$$HP = \frac{5.55 \times (118.2)^3 \times .00237 \times D^{2/3}}{35,000}$$

$= .62\ D^{2/3}$, and by combining with equation (1),

$D - 76.5\ D^{2/3} = 42,000.$

From figure 1, D = 570,000 lb.

$D^{2/3} = 6900.$ Air volume = 7,470,000 ft.^{3}

HP = .62 × 6900 = 4290.

This example shows the great cost of increasing the speed while maintaining the same hours of endurance at the higher speed. On the other hand, the speed could be quite easily increased to 70 knots, if the endurance remains 60 hours at 60 knots.

The horsepower at 60 knots is only 63% of that required for 70 knots, and the weight of power plant and fuel per horsepower is therefore 8 + (.63 × .6 × 60) = 30.7 lb. The fundamental equations are therefore:

15,000 + 30.7 (HP) = .357 D

and HP = $.62\ D^{2/3}$, whence

$D - 53.3\ D^{2/3} = 42,000$

D = 260,000 lb. $D^{2/3} = 4080$

HP = .62 × 4080 = 2530

Air volume = 260,000/.07635 = 3,400,000 ft.^{3}

The method may be used also to find the extent to which the size may be reduced by structural improvements, as follows:

Problem 3. Suppose that by an improved design, the structural weight can be reduced 10% in comparison with the conditions assumed in Problem 1. The fixed weights exclusive of power plant, power cars, and fuel system become .27 D, and assuming as in Problem 1 that 60 knots is required for 60 hours,

$$15{,}000 + 44\ (HP) = .387\ D$$

and $HP = .39\ D^{2/3}$, whence

$$D - 44.4\ D^{2/3} = 38{,}800$$

$$D = 180{,}000 \text{ lb.} \qquad D^{2/3} = 3200$$

$$\text{Air volume} = 180{,}000/.07635 = 2{,}360{,}000 \text{ ft.}^3$$

$$HP = .39 \times 3200 = 1250.$$

By comparison with the results of Problem 1, it is found that a 10% saving in fixed weights exclusive of power plant, permits a 16% reduction in volume and 11.3% in horsepower.

A 10% improvement in the resistance coefficient may also be tested in a similar manner. Repeating the conditions of Problem 1, let K be increased by 10% from 35,000 to 38,500. Then

$$HP = .355\ D^{2/3}$$

$$D - 43.75\ D^{2/3} = 42{,}000$$

$$D = 185{,}000 \text{ lb.} \qquad D^{2/3} = 3250$$

$$\text{Air volume} = 185{,}000/.07635 = 2{,}420{,}000 \text{ ft.}^3$$

$$HP = .355 \times 3250 = 1150.$$

If it is required to operate at a high altitude, the conversion factor, air volume = $D/.07635$, still holds, but in estimating the weights, the allowance made for air and gas must be increased, as in the next problem.

Problem 4. Determine the volume of a nonrigid airship to carry a military load 1000 lb. at 4000 ft. altitude at 50 knots (84.5 ft./sec.) for 10 hours. Ship to be inflated with hydrogen which has a lift of .068 lb./ft.^{3} in the standard atmosphere at sea level. Starting a flight at 4000 ft. fully inflated, corresponds to 88.8% inflation at sea level; the weight of air and gas at sea level is therefore

$$[.112 + .888\ (.07635 - .068)/.07635]\ D = .209\ D$$

It may seem cumbersome to calculate the weight of air and gas in this manner instead of correcting D for the altitude, but it should be remembered that since the structural weights are to be taken as fractions of D, it is important that D should be taken as a constant fraction of the air volume.

From data on previous ships, the fixed weights exclusive of power plant and fuel system equal .4D, and crew, stores, and ballast amount to .1D. There remains for the power plant, fuel and military load $(1 - .209 - .4 - .1)\ D = .291\ D$. Taking the weight of the power plant as 6 lb./HP, and the weight of the fuel, oil, and containers as 0.6 lb./HP.H, the total weight of power plant, fuel, and fuel system is $[6 + (10 \times .6)]\ HP = 12\ (HP)$, and the equation is obtained:

$$1000 + 12\ (HP) = .291\ D.$$

From existing data, $K = 22,000$, and at 4000 ft. altitude,

$\rho = .888 \times .00237 = .0021$ slugs, therefore,

$$HP = \frac{5.55 \times (84.5)^3 \times .0021 \times D^{2/3}}{22,000}$$

$$= .32\ D^{2/3}$$

Combining these equations as before,

$$D - 13.2\ D^{2/3} = 3340$$

From figure 2, $D = 9100$ lb. $D^{2/3} = 435$

Air volume = 9100/.07635 = 119,000 ft.^{3}

HP = .32 × 435 = 139.

The method may also be used to find the military or commercial load which can be carried by an airship of given size at a given speed and endurance, as follows:

Problem 5. Find the commercial load which can be carried by a rigid airship of 5,000,000 ft.^{3} air volume, at 4000 ft. altitude, inflated with helium lifting .064 lb./ft.^{3} in standard atmosphere at sea level, and having a speed of 70 knots and an endurance of 24 hours. Given $K = 35,000$, and fixed weights exclusive of power plant = .3 D crew, stores and ballast = .05 D. Power plant = 8 lb./HP, fuel = 0.6 lb./HP.H, whence total weight of power plant and fuel = [8 + (.6 × 24)] HP = 22.4 HP

D = .07635 × 5,000,000 = 382,000 lb.

Assuming that when fully inflated the gas cells occupy 95% of the air volume, the volume of gas when 88.8% inflated at sea level (to allow for 4000 ft. altitude) is .95 × .888 = .844

times the air volume, and the weight of the air and gas is

$$[.155 + .844\ (.07635 - .064)/.07635] \times D = .293\ D$$

$$HP = \frac{(118.2)^3 \times .0021 \times (5,000,000)^{2/3}}{35,000}$$

$$= 2900$$

The total weight of the power plant, power cars, fuel and fuel system is $22.4 \times 2900 = 65,000$ lb. The weight available for commercial load is

$$382,000\ (1 - .293 - .5 - .05) - 65,000 = 71,500\ \text{lb.}$$

Choice of Dimensions for any Desired Air Volume.

Wind tunnel experiments indicate that the least resistance for a given volume is obtained with a length/diameter diameter ratio of a little less than 5, but with ratios from 4 to 6 there is very little change in efficiency. For nonrigid airships these ratios are very suitable, and the prismatic or cylindric coefficient, i.e., the ratio of the actual air volume to the volume of a prism having the largest cross-section airship, varies from 0.60 to 0.66, approximately.

The volume of an airship of circular cross-section = $2\ k\ r\ \pi\ R^3$,

where R = the radius of the largest cross-section.

k = the prismatic coefficient,

r = the length/diameter ratio.

The dimensions may be calculated by application of this formula, assuming arbitrary values of k and r.

Example: Find the length and diameter of a nonrigid airship of 200,000 ft.^{3}, volume assuming $k = .62$, and $r = 4.8$.

$$R^3 = \frac{200,000}{2 \times .62 \times 4.8 \times \pi} = 10,700 \text{ ft.}^3$$

$$R = 22 \text{ ft.}$$

$$\text{Diameter} = 2\,R = 44.0 \text{ ft.}$$

$$\text{Length} = 9.6\,R = 211.5 \text{ ft.}$$

In a rigid airship, it is usually desirable to increase the length beyond five diameters in order to space the cars properly, and to facilitate handling upon the ground, and to prevent excessive weight of the gas cells and transverse frames. Sometimes shed accommodations also influence or dictate the choice of length and diameter. When for practical reasons it is desired to have more than five diameters to length, the designer has the choice of inserting some parallel middle body, or retaining a continuously curved form by increasing the station spacing. To determine the relative merits of these two possibilities, two interesting series of tests were carried out in the wind tunnel of the Bureau of Construction and Repair at the Navy Yard, Washington, D. C. In the first series of tests various lengths of parallel middle body were inserted between the bow and stern of a model of the C class nonrigid airship. The results are fully described in the National Advisory Committee for Aeronautics Report No. 138, entitled "The Drag of C Class Airship Hull with Varying Length of

Cylindric Midships." The tests showed that a length of parallel middle body up to one diameter made practically no change in the resistance coefficient; and three diameters of parallel middle body increased the resistance coefficient by only 7.6%.

The other series of tests was on models of the C class airship with various spacing of the ordinates, giving lengths of from 2 to 10 diameter, without parallel middle body. The results of this series of tests have not been published, but it was found that increasing the length/diameter ratio from the 4.6 of the C class to 8.0 resulted in an increase of 13.2% in the resistance coefficient. The curve of the resistance coefficient was found to pass through a minimum value with a fineness or length/diameter ratio of about 4.3, or very close to what was actually used in the C class.

Comparison of the results of these two sets of tests indicate that when it is desired to increase the fineness ratio beyond about 4.5, the additional length should be obtained by inserting parallel middle body rather than by increasing the spacing of the ordinates.

It is obvious that the practical merits of the problem, aside from purely aerodynamic considerations, are also very much in favor of parallel middle body; the construction will be simpler and less expensive and the overall dimensions of the ship with a given volume and fineness ratio will be less.

The air volume of an airship hull with parallel middle body equals $2 \pi R^3 (kr_1 + r_2)$ where R is the radius of the maximum cross-section, k is the prismatic coefficient of the tapered fore and after bodies taken together, r_1 is their combined length/diameter ratio, and r_2 is the corresponding ratio for the parallel middle body. It follows that

$$R^3 = \frac{\text{volume}}{2 \pi (kr_1 + r_2)}$$

From this equation the dimensions required for any given volume and characteristics of bow and stern and proportion of parallel middle body may be determined.

Example: Find the length and diameter of a rigid airship of 5,000,000 ft.^{3} air volume, in which the tapered bow and stern have a length of 4.6 diameter and a prismatic coefficient of 0.60, and the parallel middle body is three diameters long.

$$R^3 = \frac{5,000,000}{2 \pi [(.6 \times 4.6) + 3.0]}$$

$$= 138,000$$

$$R = 51.6$$

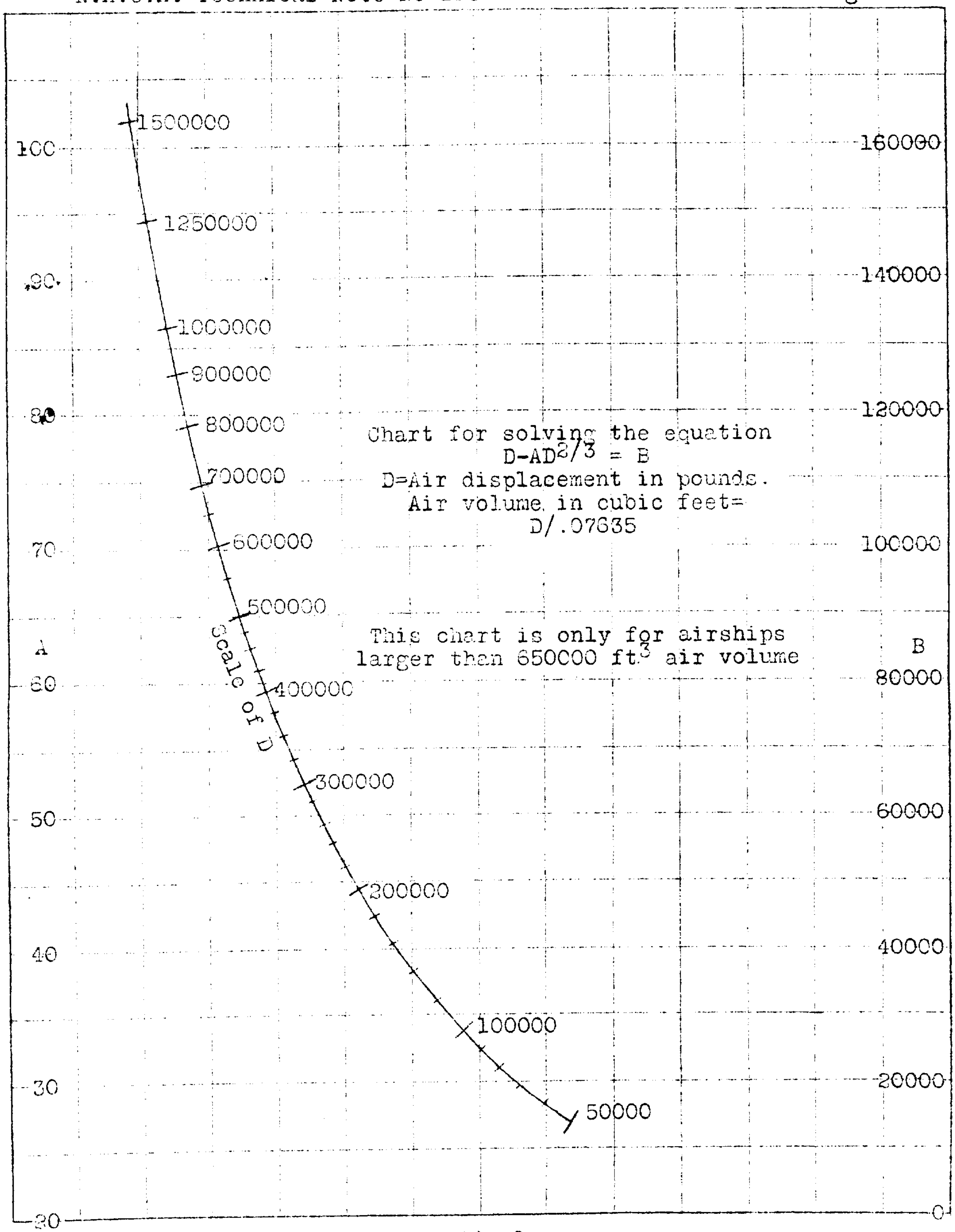
Length = 15.2 × 51.6 = 785 ft.

Diameter = 2 × 51.6 = 103.2 ft.

Conclusions

The foregoing method of calculating the size and horsepower required for an airship of any specified performance depends on existing data, and as this data becomes more complete, the method will become increasingly accurate and flexible; that is, more applicable to new and unusual types of airships.

One of the principal uses to which the method can be applied is to show the variation in size necessary when varying some one factor of the performance requirements, keeping the other factors constant.



1500000
1250000
1000000
900000
800000
700000
600000
500000
400000
300000
200000
100000
50000
Scale of D
100
90
80
70
A
60
50
40
30
20
160000
140000
120000
100000
B
80000
60000
40000
20000
0
Chart for solving the equation
$D-AD^{2/3} = B$
D=Air displacement in pounds.
Air volume in cubic feet=
D/.07635
This chart is only for airships larger than 650000 ft.^{3} air volume

Fig.1

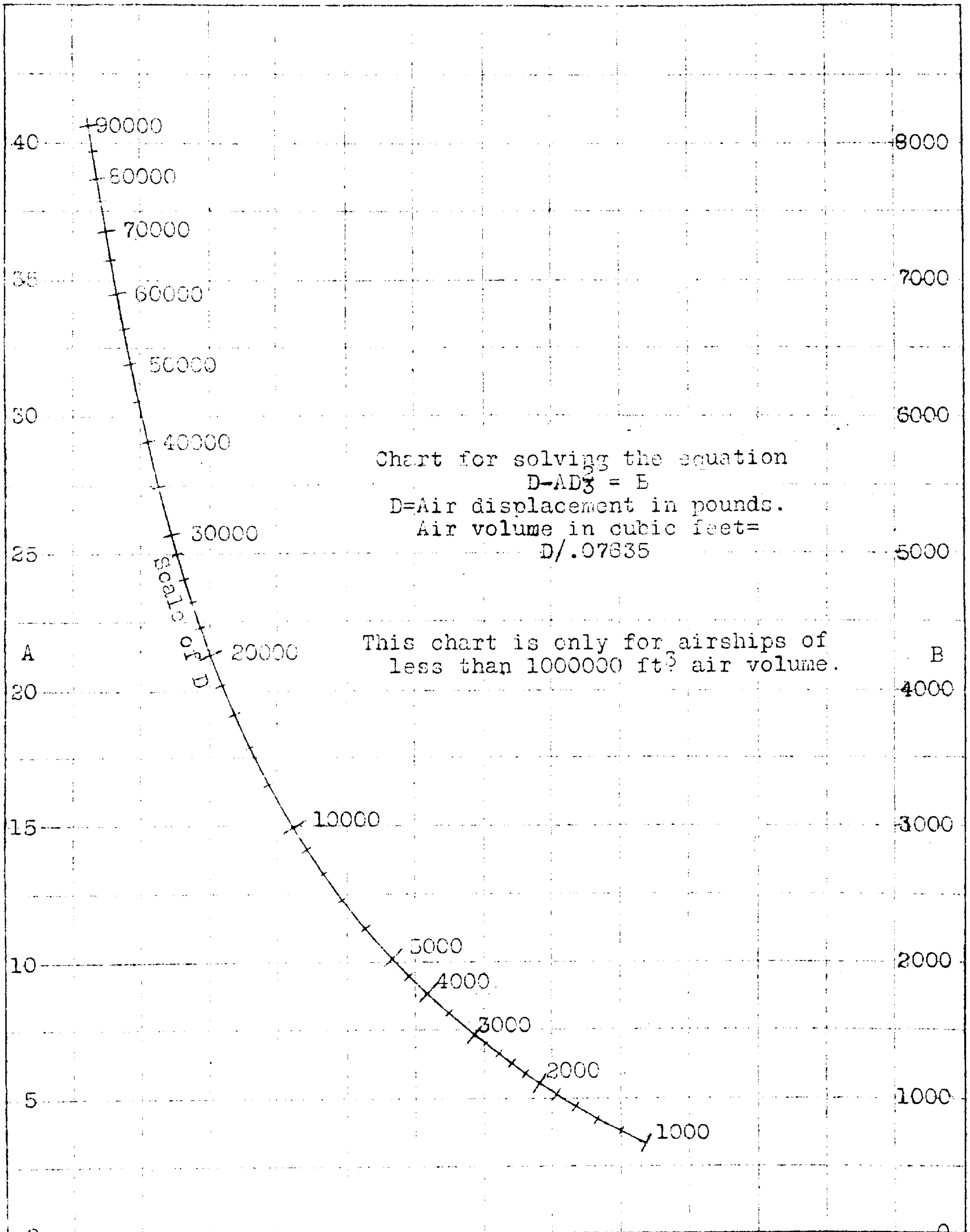


Chart for solving the equation
$D-AD^{\frac{2}{3}} = B$
D=Air displacement in pounds.
Air volume in cubic feet=
D/.07635
This chart is only for airships of
less than 1000000 ft^3 air volume.
Scale of D
90000
80000
70000
60000
50000
40000
30000
20000
10000
5000
4000
3000
2000
1000
A
40
35
30
25
20
15
10
5
0
B
8000
7000
6000
5000
4000
3000
2000
1000
0

Fig.2

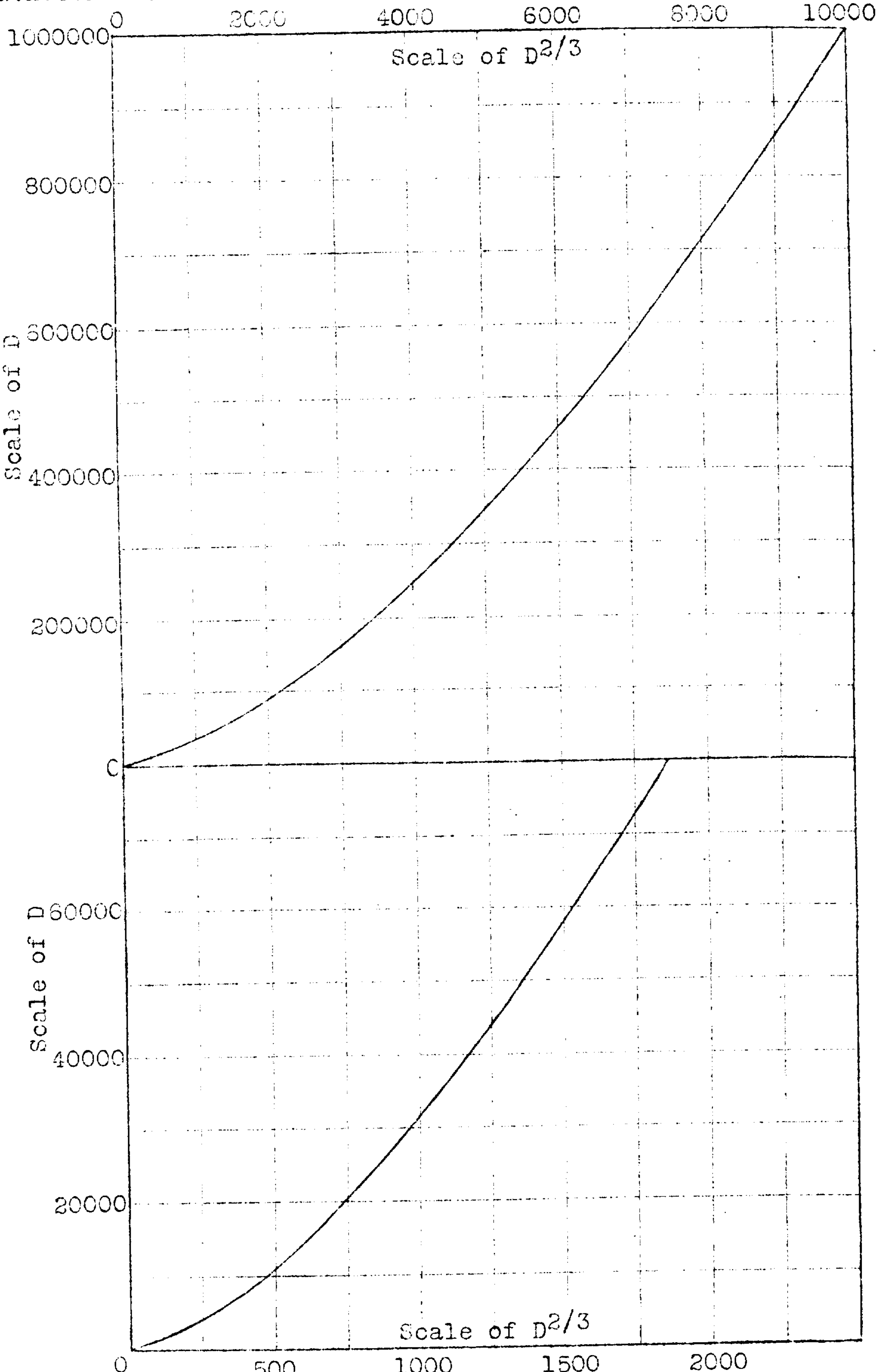


Fig.3 Chart for finding $D^{2/3}$ when D is known.